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Short Communication

Low-velocity impact response of woven Kevlar/epoxy laminated composites reinforced with multi-walled carbon nanotubes at ambient and low temperatures

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ABSTRACT

In this article, the low-velocity impact response of woven Kevlar/epoxy laminated composites enhanced with different weight percentages (⩽1%) of multi-walled carbon nanotubes (MWCNTs), was investigated under ambient (27 °C) and low temperature (−40 °C) conditions. Energy profile diagrams (EPDs) were employed to determine the penetration threshold of Kevlar/epoxy laminated composites. In addition, the effect of MWCNTs on laminate composites was evaluated by subjecting all specimens to the same level of energy, 45 J. The time history of absorbed energy, deflection and velocity are measured and some parameters such as stiffness bending, penetration limit and maximum deflection, for both composites and nanocomposites at ambient and low temperatures are reported. Results showed a remarkable dependency of damage formation on temperature and contents of MWCNTs. It was concluded that the MWCNTs was improved the impact response and was restricted the damage size in the woven Kevlar fiber composites at ambient and low temperature. The addition of 0.5% MWCNTs resulted in about 35% increase in energy absorption at ambient temperature, and the addition of 0.3% MWCNTs increased the absorbed energy capability about 34% at low temperature.

1. Introduction

Laminated polymer-based composite materials have been assigned a wide range of aspects of research in many advanced technologies, such as aerospace, military, marine and automotive industry, due to their high strength, great stiffness and low density. However, laminate composite structures have many superior advantages, the high susceptibility of damage to high-velocity or low-velocity impact is a conventional character of these materials. Hence, many investigations on the impact behavior of laminated composites at ambient or low temperature conditions have been performed [1–7]. Low-velocity impact is the source of various types of damages such as matrix cracking, delamination, fiber breakage and even perforation of fiber–matrix surface [8] in laminated polymer matrix composites. For this reason, although there exist some researches about the effect of high velocity impact on laminated composite materials, most of them focused on low-velocity impact of these materials. For instance, Aktas et al. [9] experimentally investigated the effect of different fabric layers on impact and after impact behavior of layer fabric composites subjected to low-velocity impact. They determined the perforation threshold of E-glass/epoxy composite plates containing different layer fabrics as plain weave (1D), double (2D), and triple (3D) layer fabrics. Another research was performed by Atas et al. [10] who carried out an experimental investigation on low velocity impact of composite plates prepared by vacuum assisted resin infusion molding (VARIM) and hand lay-up processes. It was found that the perforation threshold of intact samples is higher than the repaired samples.

Furthermore, there are some researches on the effect of low velocity impact at low temperature conditions such as Gómez-del Río et al. [11]. Who examined the response of carbon fiber-reinforced epoxy matrix (CFRP) laminates with different stacking sequences to impact loading in low temperature conditions [11]. Impact and post impact response of laminated composites at low temperature was obtained by Ibekwe et al. [12] who showed the significant role of temperature on the low velocity impact responses. Icten et al. [13] studied the effect of low temperature on impact response of quasi-isotropic glass/epoxy laminated plates. In addition, Salehi-Khojin et al. [14] investigated the role of temperature (from −50 °C to 120 °C) on low velocity impact properties of Kevlar/fiber glass composite laminates. Also, Sayer et al. [15] presented an experimental investigation on the impact responses of hybrid composites (carbon–glass fiber/epoxy) under

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various temperatures from −20 °C to 60 °C until complete perforation.

Few works have been performed concerning to nanoparticles effect on low-velocity impact of laminate composite materials. Avila et al. [16] considered the behavior of nanostructured laminate plates under low-velocity impact loading. It was found that the presence of intercalated nanoclays into laminates led not only to an enhancement on stiffness but also an increase on impact resistance/fracture toughness. In addition, they showed failure mechanisms, were changed from interlaminar to intralaminar [16]. Hosur et al. [17] presented a low-velocity impact response of woven carbon/epoxy–nanoclay composites. It was showed that all the nanophased composites exhibited lower level of impact damage when compared with the control samples even though there was not much change in the impact response [17]. Iqbal et al. [18] investigated the influence of nanoclay on the impact damage resistance of carbon fiber-epoxy composites using the low-velocity impact and compression after impact (CAI) tests. It was found that adding nanoclay in the matrix improved the impact damage size and shear stiffness of the matrix material, giving rise to a higher resistance to fiber buckling under a unidirectional compressive load. Reis et al. [19] performed an experimental study on the impact behavior as well as damage tolerance of Kevlar/filled epoxy matrix. Two different fillers, cork powder and nanoclays Cloisite 30B, were used in order to improve the impact response of these laminates.

In recent years, carbon nanotubes (CNTs) received much attention of scientists and industries due to their high aspect ratio and excellent mechanical, electrical, and thermal properties [20,21]. CNTs are considered to be one of the most effective reinforcing fillers in fabricating high strength, light weight polymer composites because of low density, as well as superior strength and Young's modulus [22,23]. Therefore, there are some studies on the effect of CNTs on low-velocity impact of laminated composites. Kostopoulos et al. [24] investigate the influence of multi-wall carbon nanotubes (MWCNTs) on the impact and after impact behavior of carbon fiber reinforced polymer (CFRP) quasi-isotropic laminates and reported no radical difference for the delamination area or the absorbed energy per unit delamination area. The low-velocity impact response of thin carbon woven fabric composites reinforced with different weight percentages of multi-walled carbon nanotubes was investigated. It was observed that the MWCNTs enhanced the impact response, limited the damage size and energy absorption in the woven carbon fiber composites [25].

Regarding to the previous studies on low-velocity impact of laminated nanocomposites, to the best of authors' knowledge, there is no report on the effect of nonoparticles on the impact response of these materials at low temperatures. Therefore, in the present study, the effect of different percentages of MWCNT on the impact response of woven Kevlar/epoxy composites at ambient and low temperatures is investigated. The energy profile diagram was plotted for identifying the penetration threshold of Kevlar/epoxy composites. MWCNTs were dispersed in the epoxy resin by sonication technique and the samples were fabricated by hand layup laminating procedure. Scanning electron microscopy (SEM) was utilized to characterize nanostructure and microstructure. The energy–time, velocity–time and force–deflection plots were presented for both temperatures conditions. The

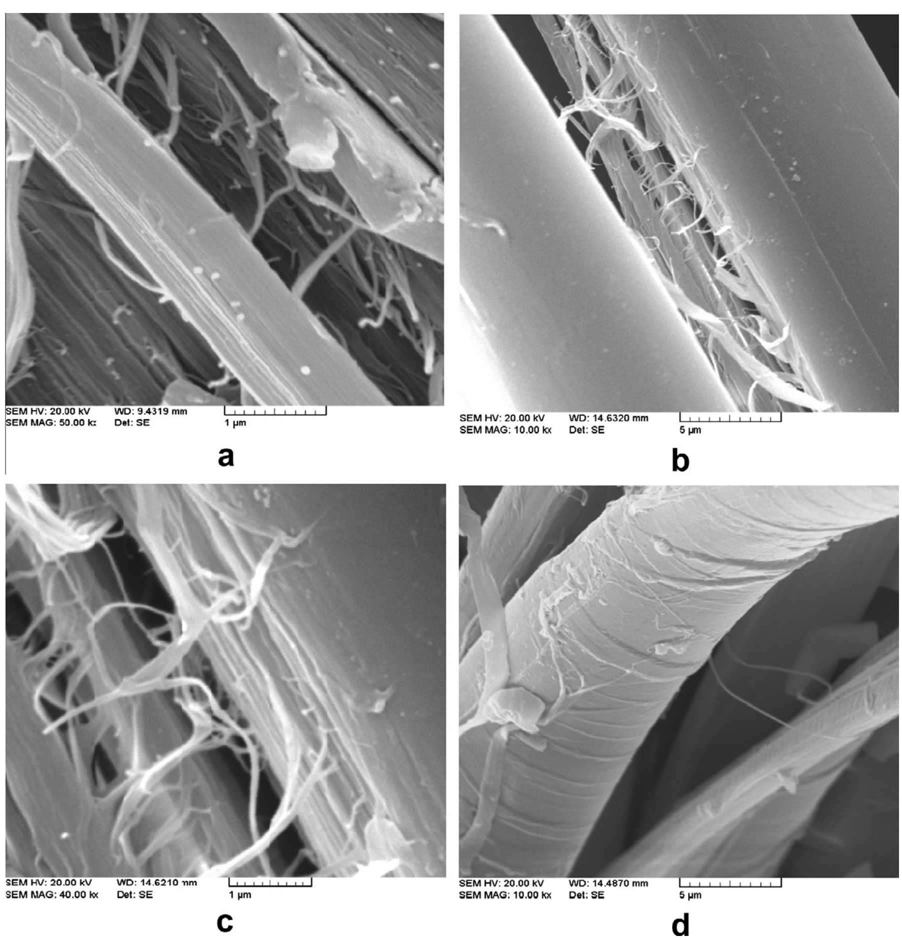

Fig. 1. SEM images of the fracture surface in MWCNTs/Kevlar/epoxy nanocomposites containing (a) 0.3 wt.% (b and c) 0.5 wt.% (d) 1.0 wt.% of MWCNTs.

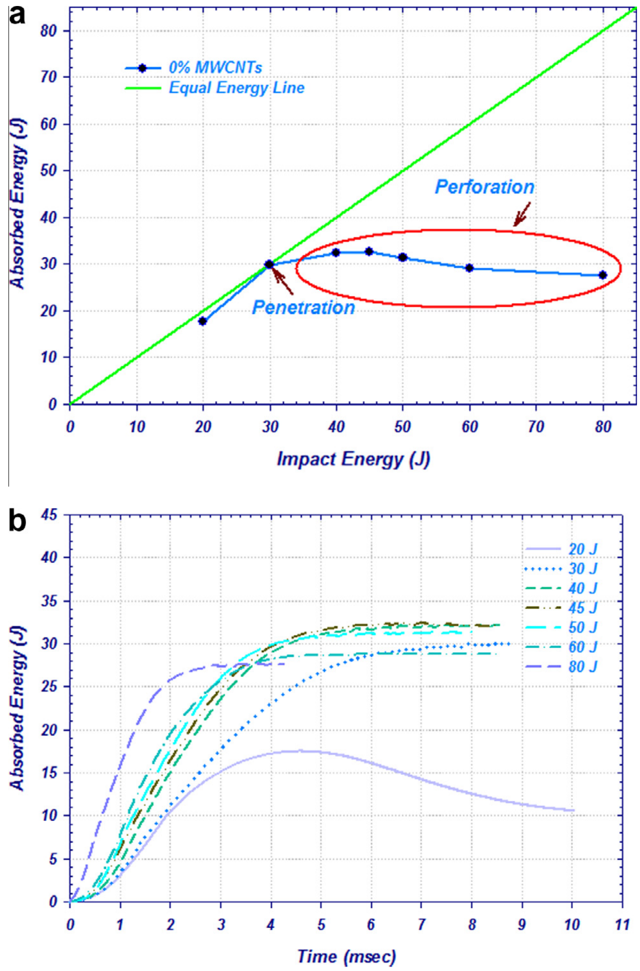

Fig. 2. (a) Energy profile diagram of Kevlar/epoxy laminate composite impacted at room temperature. (b) Energy–time response of Kevlar/epoxy laminate composite subjected to different levels of energy: 20 J, 30 J, 40 J, 45 J, 50 J, 60 J and 80 J at 27 °C.

size of damaged region was evaluated at ambient and low temperatures.

2. Materials and experimental techniques

2.1. Manufacturing of nanocomposite laminates

The nanocomposite laminates were manufactured from bi-directional woven Kevlar fabrics and MWCNTs filled epoxy resin. The resin was produced by AXON (FRANCE) EPOLAM 2002 cross-linked epoxy. The mixing ratio was 100:12 parts by weight as recommended by the vendor. The Kevlar fiber woven plain fabrics (AK502 supplied by COLAN industrial Co., Australia) with average fiber areal weight (FAW) of 175 g/m^2 were used as the primary reinforcement for composite laminates. MWCNTs were produced by 3302 Nano Research, Inf in USA by chemical vapor deposition (CVD) method. The inside diameter of CNTs was 5–10 nm and the outside diameter was 10–20 nm; the lengths of CNTs were 10–30 μm. After drying MWCNT powder in an oven to get rid of moisture, it was mixed with epoxy resin using a high shear laboratory mixer at 2000 rpm for 30 min, and then ultrasonic processor (Hielscher-UP400S, 20 kHz, and 100 W/cm^2) was used to obtain a homogeneous mixture of epoxy resin and MWCNTs. For decreasing temperature during sonication a water bath was used. The MWCNT content was chose between 0 and 1.0 wt.%. The composite sheets were prepared by hand lay-up laminating technique with stacking sequence $[0°/90°]_{2s}$ consists of 4 ply laminates of woven bi-direction Kevlar. The resin content in the resultant nanocomposite was approximately 33 wt.%. Finally the nanocomposite sheets with a nominal thickness of 2 mm were obtained. The morphological properties of the MWCNTs/woven Kevlar fabrics/epoxy nanocomposites were evaluated by scanning electron microscope (SEM) using a VEGA-TESCAN system. The dispersion of MWCNTs in the epoxy resin is depicted in Fig. 1a–d. The high resolution SEM pictures show that MWCNTs and epoxy were mixed well. Observation of the cross section of laminated nanocomposites revealed that some of the MWCNTs were aggregated. Agglomeration of CNTs

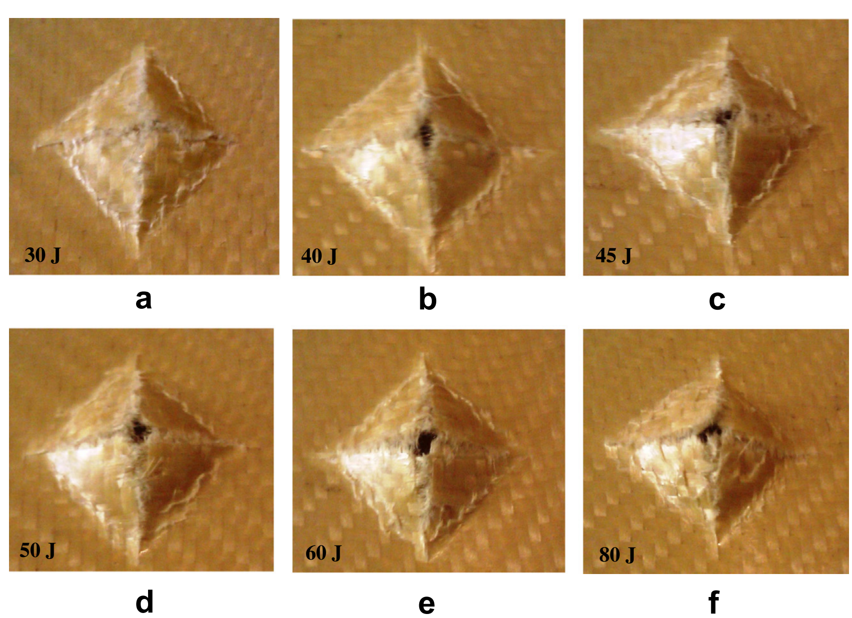

Fig. 3. Damaged samples of Kevlar/epoxy laminate composites subjected to different levels of energy at ambient.

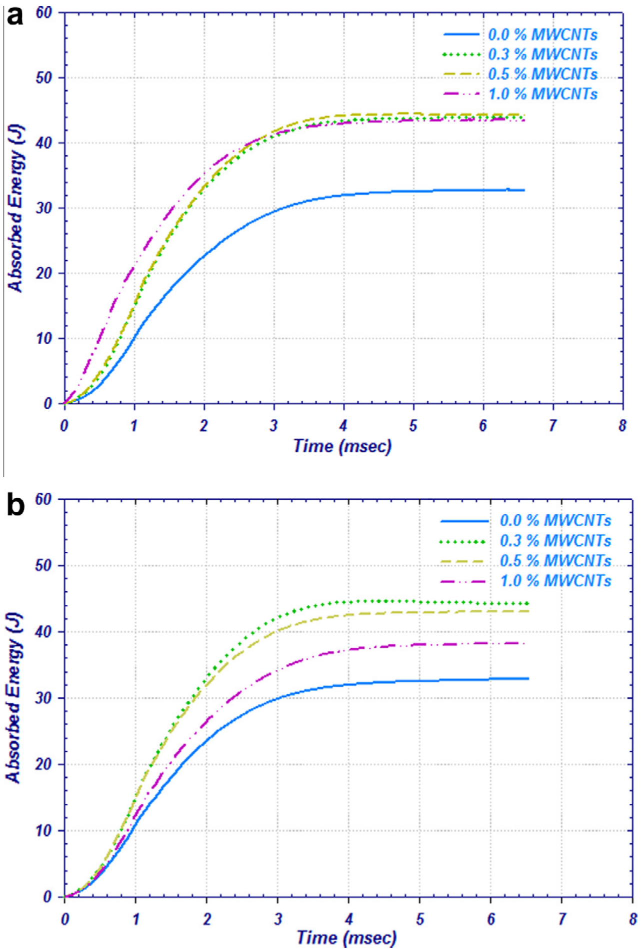

Fig. 4. Energy–time responses for various weight percentages of MWCNT for 45 J at (a) 27 °C and (b) −40 °C.

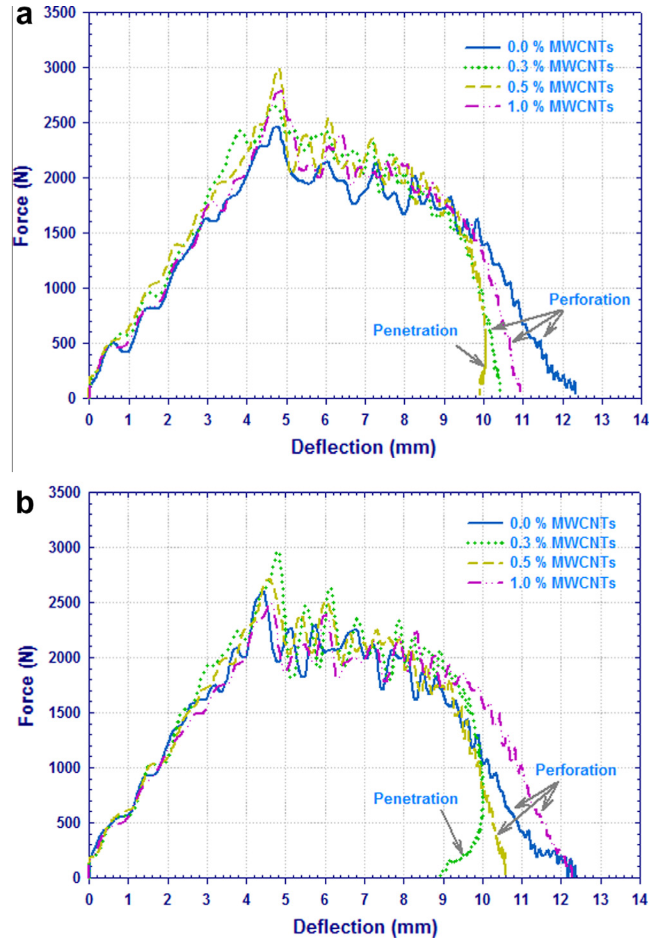

Fig. 5. Force–deflection responses for various weight percentages of MWCNT filled laminated composites subjected to 45 J energy at (a) 27 °C and (b) −40 °C.

depends on many factors, including shape, size and diameters of the tubes, as well as surface chemistry and synthesis method. The MWCNTs were mostly covered inside the epoxy matrix and a part of them could be seen as clusters on the surface of Kevlar fibers. The SEM image of the MWCNTs with 0.5 wt.% shown in Fig. 1b, c indicates that nanoparticles are well dispersed in the resin.

2.2. Impact tests and temperature conditions

The impact tests were performed according to ASTM D5628-10 at ambient and low temperature conditions. A drop tower equipped with a 7.11 kg hemispherical aluminum impactor having a diameter of 20 mm was employed. The aperture of the setup provides clamping boundary conditions and a support span of 40 mm. The impact device was a Fractovis-Instrumented falling weight tester provided by CEAST. Samples were kept about 30 min in the chamber cooled by liquid nitrogen down to −40 °C. Before the impact tests, temperature of samples was controlled by a thermometer.

3. Results and discussion

3.1. Energy profiling diagram (EPD)

The energy profile diagram (EPD) of Kevlar/epoxy laminate composite at ambient temperature is shown in Fig. 2a. This diagram is useful to identify the penetration and perforation threshold of specimens [15]. For this purpose, impact tests were performed at different levels of energy: 20 J, 30 J, 40 J, 45 J, 50 J, 60 J and 80 J at room temperature, and the absorbed energy–time curves are plotted in Fig. 2b. These results have been used to plot the energy profile diagram that shows the relationship between impact energy and absorbed energy. A diagonal line, called equal energy line [9], is drawn in Fig. 2a to represent the equality between impact and absorbed energies. The diagram shows that when the impact energy was 20 J, the data point lies below the equal line. As the impact energy increased up to 30 J, the absorbed energy is equal to impact energy. By inducting higher level of energy, the data points lie below the equal energy line again. The point at which the absorbed impact energy and impact energy are equal is considered as the penetration threshold whereas the others points shows perforation at higher levels of energy [15]. Thus, the penetration threshold of Kevlar/epoxy composite is at 30 J, and for levels of energy higher than 40 J, the composites are completely perforated. Although, this test method could be used to determine the penetration and perforation threshold of the nanocomposites, in this study, all specimens are only subjected to the same level of energy, 45 J, to investigate the effect of various contents of nanotubes on absorbed energy, bending stiffness and damage resistance of composites.

Fig. 3a–f shows the type and size of damaged area for Kevlar/epoxy composites without CNTs at ambient temperature subjected to various levels of energy, 30 J, 40 J, 45 J, 50 J, 60 J, and 80 J, respectively. As it shows, the penetration mode is obvious for specimens subjected to more than 30 J. This level of energy

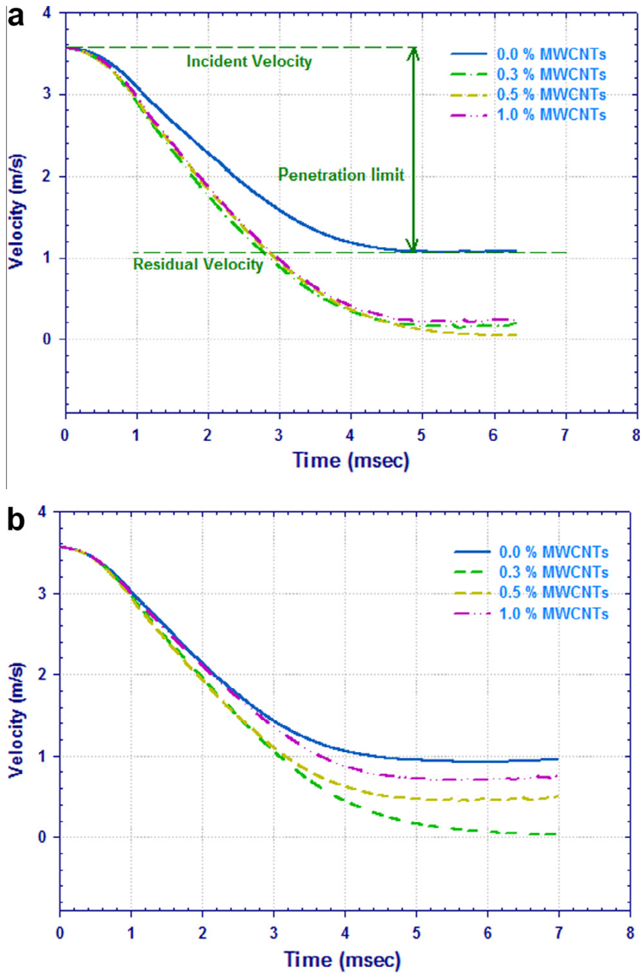

Fig. 6. Velocity–time responses for various weight percentages of MWCNT at 45 J energy at (a) 27 °C and (b) −40 °C.

is the penetration threshold for these composites. The perforation mode is a dominant mode for the specimens imposed to more than 40 J.

3.2. Energy–time response

The absorbed energy is the energy absorbed by the specimen in consequence of the formation of damage and the friction between striker and specimens [13]. The energy–time responses for various contents of MWCNT are shown in Fig. 4a and b for the case of 45 J at room and low temperatures, respectively. Fig. 4a illustrates that by adding MWCNTs, the absorbed energy increased about 30%. These results for 0.5 wt.% MWCNT are higher than those for other contents of that. Moreover, at low temperature the results show the same trend. It means the absorbed energy was increased by adding MWCNTs. However, at low temperature, 0.3 wt.% MWCNT is the optimum content for the composites. When the temperature decreases the matrix of nanocomposite becomes brittle [12], and it causes the less resistance by adding more carbon nanotube to the composites when the striker impacts the samples.

3.3. Force–deflection response

The slope of ascending section of each force–deflection curve represents the impact bending stiffness of laminated composites during impact process [26]. Such curves also demonstrate the response of composite laminates subjected to impact loading, such as rebounding, penetration and perforation [15]. The force–deflection curves for different weight percentages of MWCNT are shown in Fig. 5a and b at the same level of energy, 45 J, at room and low temperatures, respectively. Fig. 5a illustrates steeper slope and higher peak of force–deflection curve by adding MWCNT in the matrix of composites. According Soliman et. al. [25] this behavior also has been observed in the woven fabric composites incorporating with multi wall carbon nanotubes. As seen on Fig. 5a, however at 45 J the perforation mode is occurred, but by adding 0.5 wt.% MWCNTs the penetration mode is happened. Comparison of Fig. 5a with Fig. 5b shows that the curves slopes in low temperature are higher than those in ambient temperature. At low temperature, the specimens become brittle and so the bending stiffness increases [13]. Although Fig. 5b indicated higher peak force for nanocomposites up to 0.3 wt.% MWCNTs, but increasing the content of MWCNTs up to 1 wt.% decreases the peak force and bending stiffness and causes the fully perforation of the specimens.

3.4. Velocity–time response

Fig. 6 shows the velocity–time responses for different weight percentages of MWCNT at the same level of energy, 45 J at room and low temperatures. It is clear from Fig. 6 that the all composite and nanocomposite samples were penetrated. The penetration limit, obtained from the difference between incident and residual velocities [25], is shown in Fig. 6. It was observed that by adding the nanoparticles to the composites the penetration limit was increased. The results of penetration limit at low temperature compared with ambient temperature showed that the penetration limit decreased when temperature fell down. The optimum results were observed, by adding 0.5 wt.% MWCNTs in ambient temperature and 0.3 wt.% MWCNTs in low temperature. Moreover, some parameters such as the pick force, penetration energy, penetration limit, bending stiffness and maximum deflection are compared between ambient and low conditions for various contents of MWCNT in Table 1.

3.5. Damage evolution

The effect of MWCNT on the damage development of laminated composites is shown in Figs. 7 and 8, at ambient and low

Table 1
Parameters of low-velocity impact for Kevlar/epoxy laminated composites with various contents of MWCNT.

Temperature (°C)	MWCNT (Wt. %)	Peak force (KN)	Absorbed energy (J)	Penetration limit (m/s)	Bending stiffness (N/mm)	Max deflection (mm)
27	0.0	2.461	32.75	2.47	498.94	5.0
	0.3	2.646	43.92	3.37	518.42	4.8
	0.5	2.987	44.29	3.51	570.35	4.7
	1.0	2.786	43.54	3.32	514.80	4.9
−40	0.0	2.591	32.83	2.60	507.85	5.1
	0.3	2.972	44.22	3.52	574.11	4.6
	0.5	2.711	43.04	3.06	544.18	4.8
	1.0	2.496	38.28	2.80	504.02	5.0

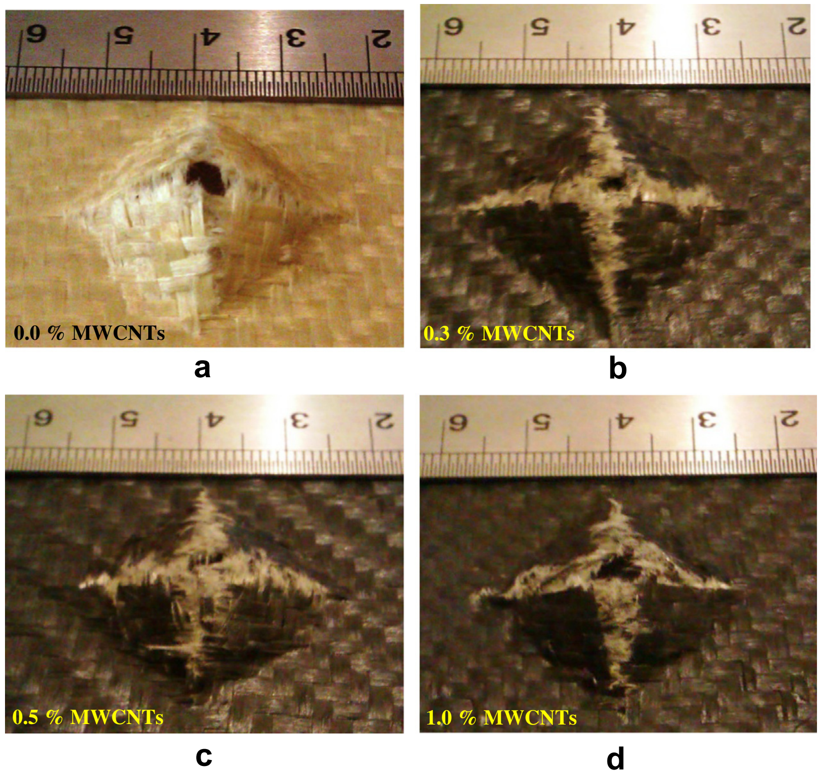

Fig. 7. Damaged samples of Kevlar/epoxy laminated composites subjected to 45 J with different contents of MWCNT: at 27 °C.

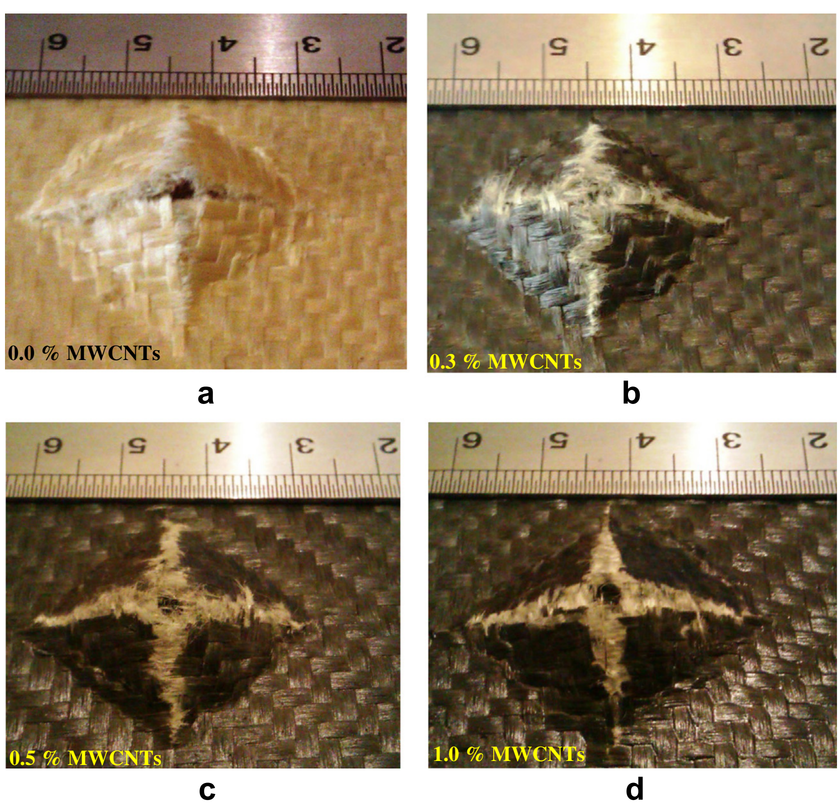

Fig. 8. Damaged samples of Kevlar/epoxy laminated composites subjected to 45 J with different contents of MWCNT: at −40 °C.

temperatures, respectively. Fig. 7a is an example of Kevlar/epoxy composites subjected to 45 J at room temperature. As seen in Fig. 7b, by adding MWCNTs up to 0.3 wt.%, the interaction between MWCNTs and matrix prevents the development of damage around the impact area.

Fig. 7c also shows smaller size of damaged area at 0.5 wt.% MWCNT in comparison with 0.3 wt.%. The effect of adding nanotube on the size of damage in woven carbon composites shows that the adding nanoparticles decrease the damage area [25]. According to Fig. 7d, by adding 1 wt.% MWCNTs to composites, aggregation of MWCNTs would weaken matrix–fiber interfacial interactions, making the size of damage region larger than samples with less amounts of MWCNT. Fig. 8a shows an example of damage at low velocity impact in Kevlar/epoxy laminates composites at low temperature. As compared with Fig. 7a, it was observed that the delamination area at low temperature is larger than that at ambient temperature. It is because of when the temperature decreases, the matrix become brittle, and cracking can propagate faster when striker inducted energy to the surface of sample plates [12]. Fig. 8b shows that by adding 0.3 wt.% MWCNTs, the delamination area disappeared, and also the size of damage area gets smaller than other composites and nanocomposites samples at low temperature conditions. In Fig. 8c, the impact tests were performed on 0.5 wt.% MWCNT-added laminated composites at low temperature. By comparing Fig. 8a with Fig. 8c, it was noticed that adding 0.5 wt.% MWCNTs can reduce the size of damage area not as much as 0.3 wt.% MWCNTs, at low temperatures. Fig. 8d also shows that because of being some part of nanotubes agglomeration in 1 wt.%, the capability of matrix for preventing of damage development gets decreased.

4. Conclusions

This experimental study investigated the low-velocity impact response of woven Kevlar/epoxy laminated composites reinforced with different weight percentages of MWCNT at ambient and low temperature conditions. First of all, the energy profile diagram was plotted to find the perforation and perforation thresholds of woven Kevlar/epoxy laminated composites at room temperature. It was shown that the perforation threshold was 30 J and after inducting 40 J, the samples were fully perforated. Then, by adding nanotubes of different weight percentages into the composite, the effect of MWCNTs on laminated composites subjected to the same level of energy, 45 J, at room and low temperatures was investigated. The significant findings from the present investigation are as follows:

- The absorbed energy of Kevlar/epoxy laminated composites at room temperature get increased up to about35% by adding 0.5 wt.% MWCNTs into the matrix, whereas at low temperature the absorbed energy get increased up to about 34% by adding 0.3 wt.% MWCNTs.
- The bending stiffness get increased up to 15% by adding 0.5 wt.% MWCNTs at ambient temperature and up to about 13% by adding 0.3 wt.% MWCNTs at low temperature. Moreover, the lower the temperature, the greater the bending stiffness.
- The penetration limit of laminated composites get increased up to about 40% by adding 0.5 wt.% MWCNTs at ambient temperature, and up to about 35% by adding 0.3 wt.% MWCNTs at low temperature.
- By considering damage transition of laminate composites, it was observed that adding MWCNTs to composites makes the size of damage decreased, and the delamination area around impact point diminished, because by bridging of nanotubes between the matrix and Kevlar fibers, the resistance of matrix to damage propagation gets increased.

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